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ABSTRACT

Steel piles are known for their high resistance to driving and handling, as well as their large lateral stiffness. Difficulty of driving depends on the subsurface conditions, pile type, and type of impact hammer used to drive piles. This case history presents observations of pile construction for a bridge widening retrofit in the city of Irwindale. The proposed foundations consisted of twenty seven 14-inch-diameter Caltrans Standard Plan B2-5 Alternative V closed-end pipe piles with quarter-inch thick steel sections. Piles were 35 feet in length and were designed to be driven piles. Subsurface investigations indicated the soils consisted of silty gravels with sand and silty sands with gravel in a medium dense condition. Excavations for the pile cap revealed a large amount of cobbles and boulders unknown during design. Difficult driving conditions resulted in failure of several closed-end steel pipe piles. Attempts at driving open-ended steel pipe piles also failed. Mushrooming of pile tops as well as buckling and shearing of piles was observed during pile driving. Failed piles were extracted for further examination. An alternative method of installation was developed to minimize the impact to the original scope of work and utilize materials already furnished for the job. The alternative method of installation consisted of pre-drilling 20-inch-diameter holes to pile tip elevation, and placing the steel shells in open excavations without driving. High-strength grout was used to fill in the annular space between the steel pipe pile and the surrounding soils. Analysis was performed to ensure the alternative installation method did not adversely affect the required load capacity of the piles.

INTRODUCTION

There has been a recent increase in the use of steel pipe piles for bridge retrofits within Los Angeles County. Advantages of using steel pipe piles include high resistances to driving and handling, as well as a large lateral stiffness (Salgado, 2008). Difficulty of driving depends on a variety of factors, including size of the impact hammer, pile type, and subsurface conditions. Drivability of closed-end (displacement) pipe piles versus open-ended (non-displacement) pipe piles varies. Difficult subsurface conditions, such as the presence of large cobbles and boulders, can adversely impact or even completely halt pile driving operations.

Maintaining the structural integrity of piles during driving is critical throughout construction. Despite its high strength and ductility, steel piles can be susceptible to damage if too much energy is exerted on piles by an impact hammer and subsurface conditions are not conducive. Observations must be made by qualified personnel as part of the quality control program, to ensure that the integrity of the steel is not compromised during pile driving.

This case study presents observations of pile construction for a bridge retrofit in the city of Irwindale, California. This paper will provide an overview of the retrofit design, subsurface conditions, challenges during construction, the alternative method of installation, and concluding remarks on pile construction.

PROJECT DESCRIPTION

The bridge is located in the County of Los Angeles, where Los Angeles Street crosses Big Dalton Wash, at the border between the City of Irwindale and the City of West Covina. Contract plans (LACDPW, 2007) show a single-span bridge that is approximately 110 feet in length and 40 feet in width. The proposed retrofit was to widen the bridge for additional lanes of traffic. Foundations consisted of 27 driven steel pipe piles. The piles were to be 14-inch-diameter closed-end pipes with quarter-inch thickness, as specified on Caltrans Standard Plan B2-5 Alternative V (Caltrans, 2006). Fourteen piles were to be constructed at the westerly abutment and 13 piles at the easterly abutment. Each pile was designed for a nominal axial capacity in compression of 280 kips at a minimum embedment depth of 35 feet.

SUBSURFACE CONDITIONS

A geotechnical investigation (LACDPW, 2003) for the bridge widening project was performed in 2003, and consisted of drilling two 6.5 inch diameter hollow stem borings. Borings were each drilled to a depth of 25 feet below ground surface where, according to the report, coarse gravels and cobbles impeded further exploration. Boring logs presented in the final report indicated that on-site soils consist predominantly of silty gravels with sand and silty sands with gravel in a medium dense condition. Results in 4 out of the 5 sieve analyses tests, performed on samples taken at varying depths, indicated that 50 percent or more of the materials were retained by the number 4 sieve. Standard Penetration Test (SPT) blow counts were not provided.

The geotechnical report identified the presence of coarse gravel and boulders; however it did not describe the anticipated size or frequency of these materials. This was likely unknown due to the type of investigation performed. The small diameter hollow stem borings typical for this scope of geotechnical investigation provide only a small sample of subsurface conditions across the project site. It may have been possible to speculate the presence of oversize materials from refusal encountered during drilling, but it would have been difficult to determine their size without being able to collect a sample.

The geotechnical report concluded that driving piles would be difficult due to the presence of cobbles and boulder. It also concluded that cast-in-drilled-holes (CIDH) piles were not recommended due to anticipated caving and heaving.

Initial excavations and shoring installation for the pile cap uncovered large cobbles and boulders up to 2 feet in diameter. As construction progressed, more subsurface information became available through visual inspection of excavated materials. It became clear that an abundance of oversize materials were present in the subsurface (Figure 1).

Fig. 1. Cobbles and boulders encountered during initial excavation and shoring installation.

CHALLENGES DURING CONSTRUCTION

Performance of Driven Piles

Performance of driven piles depends on a variety of factors, including size of the impact hammer, pile type, and subsurface conditions. When difficulties arose installing the piles for Los Angeles Street as designed, efforts were made to install the piles with minimal change to the contractor's scope of work. This resulted in attempts to drive several different pile configurations. This provided us with an up-close look at various behaviors exhibited by failed steel pipe piles. Our observations made in the field are described in the following sections.

Impact Hammer. There are many equations used to verify the axial capacity of driven piles during construction. The County of Los Angeles uses the Modified Gates formula, in concurrence with California Department of Transportation (Caltrans, 2006) Standard Specifications:

$$R_u = [1.83 * (E_r)^{1/2} * \log(0.83 * N)] - 124 \qquad (1)$$

where:

R_u = Nominal driving resistance (kips)
E_r = Manufacturer's rating for energy developed by the hammer at the observed field drop height (ft-lbs)
N = Number of hammer blows in the last foot (blows/ft)

This equation is dependent on the type of impact hammer being used and the energy being exerted on the pile. In this case, the contractor used a Delmag 30-32 single acting diesel hammer. The hammer's operating energy range is between 35,383 feet-pounds up to a manufacturer's maximum of 69,898 feet-pounds with an operating stroke range between 5.34 and 10.57 feet (DELMAG, 2010). When the operating range is plugged into the above equation for E_r, between 8 and 18 blows per foot are required to achieve the required nominal capacity of 280 kips. Caltrans caps the maximum number of blows allowed for foot of penetration at 96, making the 8 to 18 blows per foot required for these piles a relatively low number (Caltrans, 2006). While the number of blows does fall in an acceptable range, it indicates that the hammer may have been slightly oversized for this pile configuration.

Closed-End Piles. Driving full displacement piles with closed-end bottoms was attempted at the westerly abutment (Abutment 1) over the course of a week. Piles 1 and 6 were initially predrilled, with a 14-inch-diameter solid flight auger, to a depth of 20 feet below grade. Caving was observed as oversized materials and dry sands continually fell into the holes, and the effective diameter of disturbed material increased to several feet. Difficulty driving the piles was noticed almost immediately and the predrilling depth was increased to 35 feet below grade. Refusal was defined to be when minimal penetration was observed or the piles began to go off-plumb. Despite increasing the predrilled depth, driving refusal for Piles 1 and 6 was encountered at depths of 25 and 15 feet below grade, respectively.

Significant structural damage of the steel was observed at refusal. A mushrooming effect was observed at the pile top (Figure 2). Significant buckling of the steel pipe pile was observed at the pile tip, creating an "accordion" pattern along the pile (Figure 3).

Fig. 2. Mushrooming effect at the pile top.

Fig. 3. Buckling failure of closed-end steel pipe pile viewed from inside the pile.

Open-Ended Piles. After observing the failure of closed-end piles, it was determined that subsurface conditions were not conducive for driving full-displacement piles. The steel plates were subsequently removed from the bottoms of Piles 8 and 9. This created non-displacement piles, which should have significantly less resistance to driving than full-displacement piles. Additionally, the change was not very different from the contractor's original scope of work, and allowed him to utilize equipment already mobilized for the job. Pile driving was attempted on open-ended Piles 8 and 9 after 14-inch-diameter predrilling, but refusal was encountered at depths 7 and 20 feet below grade, respectively.

Structural damage of the steel for open-ended piles was also observed at refusal. Piles were extracted and examined upon refusal. The same mushrooming effect was observed at the pile top as with closed-bottoms. Significant shearing of the steel was observed at the pile tips (Figures 4 and 5).

Fig. 4. Shearing of open-ended steel pipe pile tip after extraction.

Fig. 5. Shearing of open-ended steel pipe pile tip after extraction.

After unsuccessful attempts to drive both closed- and open-ended piles, it was determined that an alternative method of installation would be required for the piles.

ALTERNATIVE METHOD OF INSTALLATION

Public Works staff worked with the contractor to determine a feasible alternative to install piles with minimal impact to the original scope. Steel pipe piles for both abutments were already fabricated and on-site; therefore, it was preferred that any design change still use existing materials.

After a collaborative meeting with the contractor and construction inspectors, it was agreed to pre-drill larger diameter (20 inch) holes to tip elevation and place steel piles in them without driving. The annular space between the steel pipe pile and the cored hole was to be pressure-grouted and the center of the steel pipe filled per Caltrans Standard Plan B2-5 Alternative V (Caltrans, 2006). From a geotechnical standpoint, the alternative method of installation essentially created CIDH piles using the steel pipe piles as reinforcement.

Verification of Pile Design Capacities

Analysis was performed to verify that the alternative method of pile installation would still achieve the axial and lateral capacities of the original design.

Axial. The original design considered both end bearing and skin friction contributing to the total capacity of the driven pile. However, the alternative installation method effectively changed the pile from a driven displacement pile to a cast-in-drilled-hole non-displacement pile. To consider this change in the pile's load-displacement behavior, the reanalysis relied only on skin friction to provide the total pile capacity. By increasing the diameter of the piles from 14 inches to 20 inches, skin friction would be mobilizing across a larger surface area for the same length of pile. Additionally, the soil-pile interface friction would be considerably greater between a pressure-grouted slurry-to-soil contact as opposed to a steel-soil contact (NAVFAC, 1986). Based on the reanalysis, it was confirmed that the original design capacities would still be achieved with the new method of pile installation.

Lateral. The original pile layout specified that 12 of 27 piles were to be battered at an angle of 1:4 (H:V) to increase lateral capacity. It was determined that the alternative installation method would be impractical to construct battered piles due to an even higher potential for caving when drilling at an angle. Pile configurations were evaluated to determine whether the conversion of battered piles to vertical piles would adversely impact the required lateral capacity. Additional analysis was performed using the program LPile v.5.0 (Reese, 2000). By increasing the effective diameter, the moment of inertia of the pile was also increased. This resulted in a higher lateral capacity for every pile and the structural designers verified that the total lateral demand of the structure was met.

Construction Implementation

Drilling was performed using a production scale Bauer BG 24 track-mounted rotary drill rig, with a combination of solid flight auger and core barrel attachments (Figure 6). Difficult drilling conditions had been identified in the geotechnical report and were anticipated for the pre-drilling of 20 inch diameter holes. Nonetheless, the alternative method of installation was successful; however, drilling was slow and the contractor was only able to install 1-2 piles per day. As expected, it was difficult to control the caving sands and oversized materials were frequently falling into the open excavations that were difficult to remove.

At this time, the contractor elected to fabricate a specialized drill bit to complete the job. The bit was comprised of both a flight auger and a barrel (Figure 7). The tip of the auger was able to advance slightly ahead of the barrel, allowing the barrel to act as a temporary casing holding oversized material in place during drilling. This specialty bit allowed the contractor to slightly increase production of drilled holes; however, the drilling remained tedious throughout construction.

Fig. 6. Core barrel and solid flight auger.

Fig. 7. Specialty drill bit to control caving

Fig. 8. Steel pipe pile being placed into pre-drilled 20-inch-diameter hole.

All twenty-seven piles were installed successfully using this method (Figure 8). Some piles were unable to be removed and were filled with concrete and abandoned in place.

CONCLUSIONS

During the investigation, two 6.5-inch diameter hollow stem borings were drilled to determine the type of foundation for the bridge retrofit. Both borings yielded similar subsurface conditions and the designers determined that the potential for caving in granular soils precluded the use of cast-in-drilled-hole piles. As excavation for pile construction began, it became evident that the borings did not provide an entirely accurate assessment of the quantity and distribution of over-sized materials throughout the site that would impact pile installation. Despite industry standards for what constitutes an adequate subsurface exploration, there are limitations to extrapolating data from a finite number of borings.

The use of a heavy diesel hammer was unsuccessful in driving close-ended steel pipe piles to their target elevation. The presence of gravels, cobbles and boulders created heavy driving resistances that could not be sustained by the quarter-inch thick steel section. The pile collapsed in between the rigid steel plate bottom and the hammer apparatus attached at the top, creating an accordion-like pattern along the steel pile. The fragility of the quarter-inch thick steel section became more apparent when the plate bottoms were removed and the pile was driven as an open-ended steel pipe pile. Piles driven in this manner encountered refusal quickly and pile ends failed in shear as a result of heavy driving resistances. In both cases, pre-drilling 14-inch-diameter holes did not facilitate pile driving due to severe caving of the soils. Both close-end and open-ended steel pipe piles designed per Caltrans Standard Plan B2-5 Alternative V, did not perform well when driven into gravelly sands with cobbles. A pile drive-ability study could have provided additional insight as to whether the steel pipe pile was capable of withstanding the driving stresses of a heavy diesel hammer.

The eventual success of installing piles using the alternative method of drilling and casing, showed that cast-in-drilled-hole piles should not have been excluded as a viable option during design. The main challenge of installing piles with this method was to control caving soils, as identified in the geotechnical report. Caving sands are usually controlled either with slurry head or drill casings. Slurry head is most effective for wet loose sands that are caving due to the pore pressure differential between the excavation and native material. Caving of dry loose sands, cobbles, and boulders can be mitigated with a temporary or permanent casing that can be telescoped, vibrated or rotated into place. This provides a mechanism to prevent loose materials from falling into the excavation. In this case, the specialty drill bit furnished by the contractor was comprised of an auger and barrel. The auger was advanced in the hole as the barrel acted similarly to a temporary casing and prevented oversize material from falling in. While caving occurs for a variety of reasons, it can almost always be controlled using the appropriate construction method.

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